Components in wireless technology, 5XTC0

Module 7
Lecture: System level design

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Where innovation starts

Outline

- Recap
  - RF specifications
    - Gain
    - Noise Figure
    - Linearity
- Dynamic range
- System aspects & considerations
  - Standards in wireless communications
  - Modulation schemes
  - BER
  - Receiver sensitivity
  - Link budget

Learning Objectives

- Understand RF specifications
- Recap gain, noise and linearity
- Understand dynamic range of and amplifier
- Understand wireless system aspects & considerations
  - Wireless standards
  - Modulation schemes
  - Bit error rates – BER
  - Receiver sensitivity
  - Link budget

Literature

- David M. Pozar – Microwave Engineering
  - Chapter 14 “Introduction to microwave systems”
    - Paragraphs 14.1 and 14.2
  - Chapter 10 “Noise and nonlinear distortion”
- Further reading (not compulsory):
  - Behzad Razavi – RF Microelectronics
  - Chapters 1 to 4
  - Chapter 2 – RF specifications

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- **Recap**
  - **RF specifications**
    - **Gain**
    - **Noise Figure**
    - **Linearity**
    - Transceiver functions
- Dynamic range
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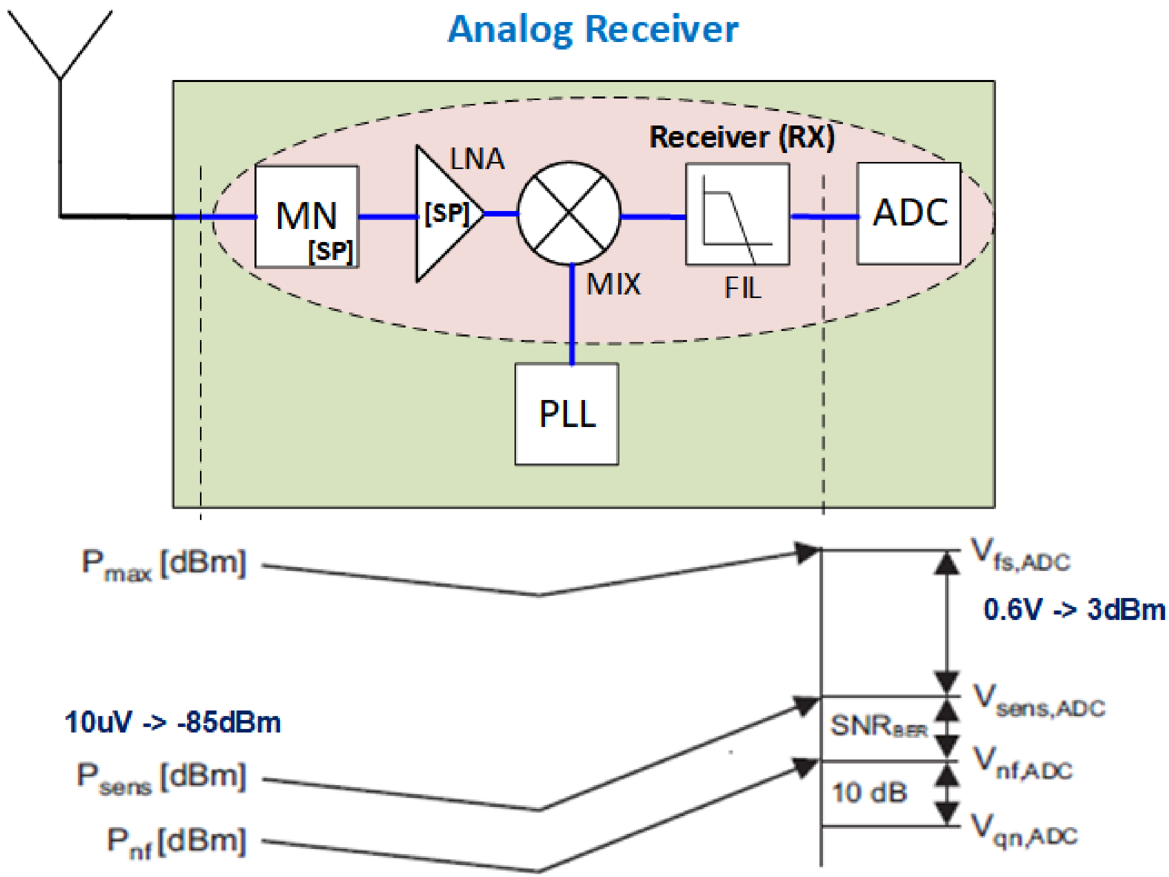
RF specifications

- Small signal
  - Gain
  - Noise figure (NF)
  - Input third-order intercept point
  - Input second order intercept point
- Large signal
  - 1-dB compression point

Linearity specifications

Why do we need gain?



- **Gain is required for signal conditioning**
- **Module 4 was dedicated to amplifier gain**

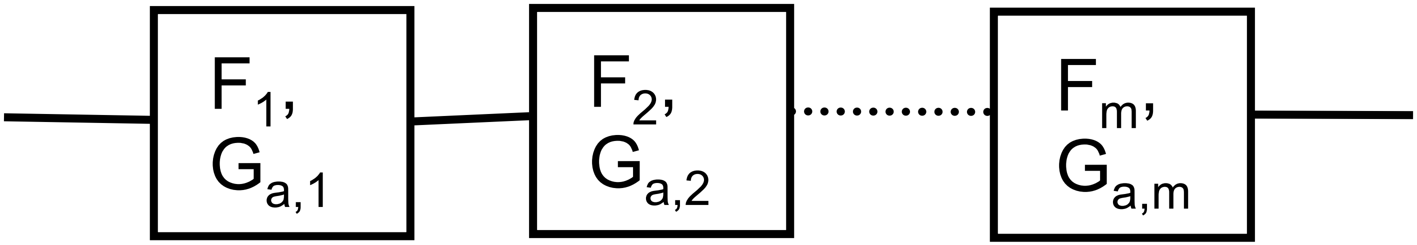
Why do we need to analyze noise?

- **Link budget allows to calculate received signal power S across a wireless link**
- **To transmit information across a wireless link, the received signal power must be significantly larger than the noise power N.**
- **The ratio between the signal power and the noise power is called “Signal-to-noise ratio” SNR:**

$$SNR = \frac{S}{N}$$

- **If we cannot distinguish the signal from the noise we cannot extract the information!**

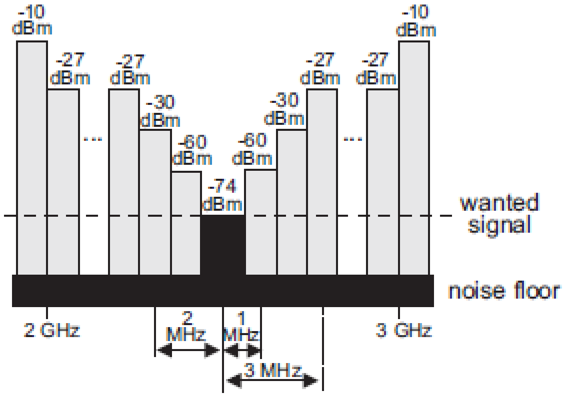
Cascaded NF: Friis' formula



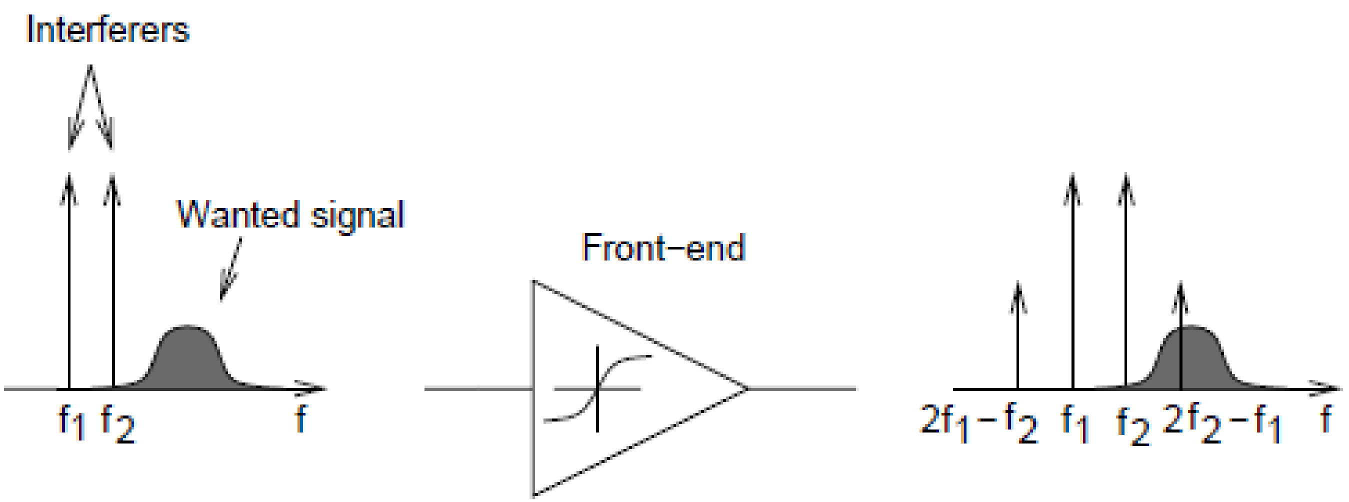
System with cascaded sub-systems with noise figure F_m and available gain $G_{a,m}$

$$F_{total} = 1 + (F_1 - 1) + \frac{F_2 - 1}{G_{a,1}} + \ldots + \frac{F_m - 1}{G_{a,1} G_{a,2} \ldots G_{a,(m-1)}}$$

Why do we need to analyse linearity?



- Typical scenario in wireless communications
- Very weak wanted signal in vicinity of strong interferers



- SNR degradation due to nonlinearity

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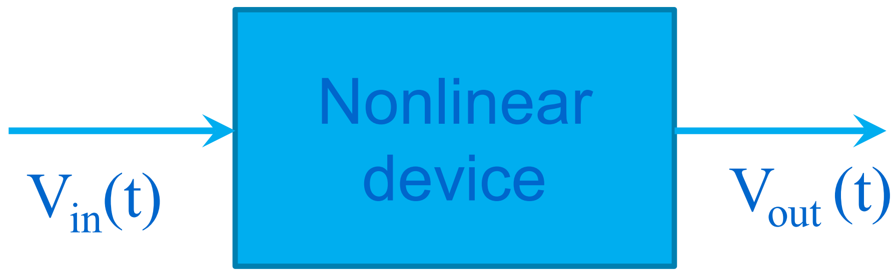
Effect of nonlinear devices on the signal

E.g. transistors, diodes



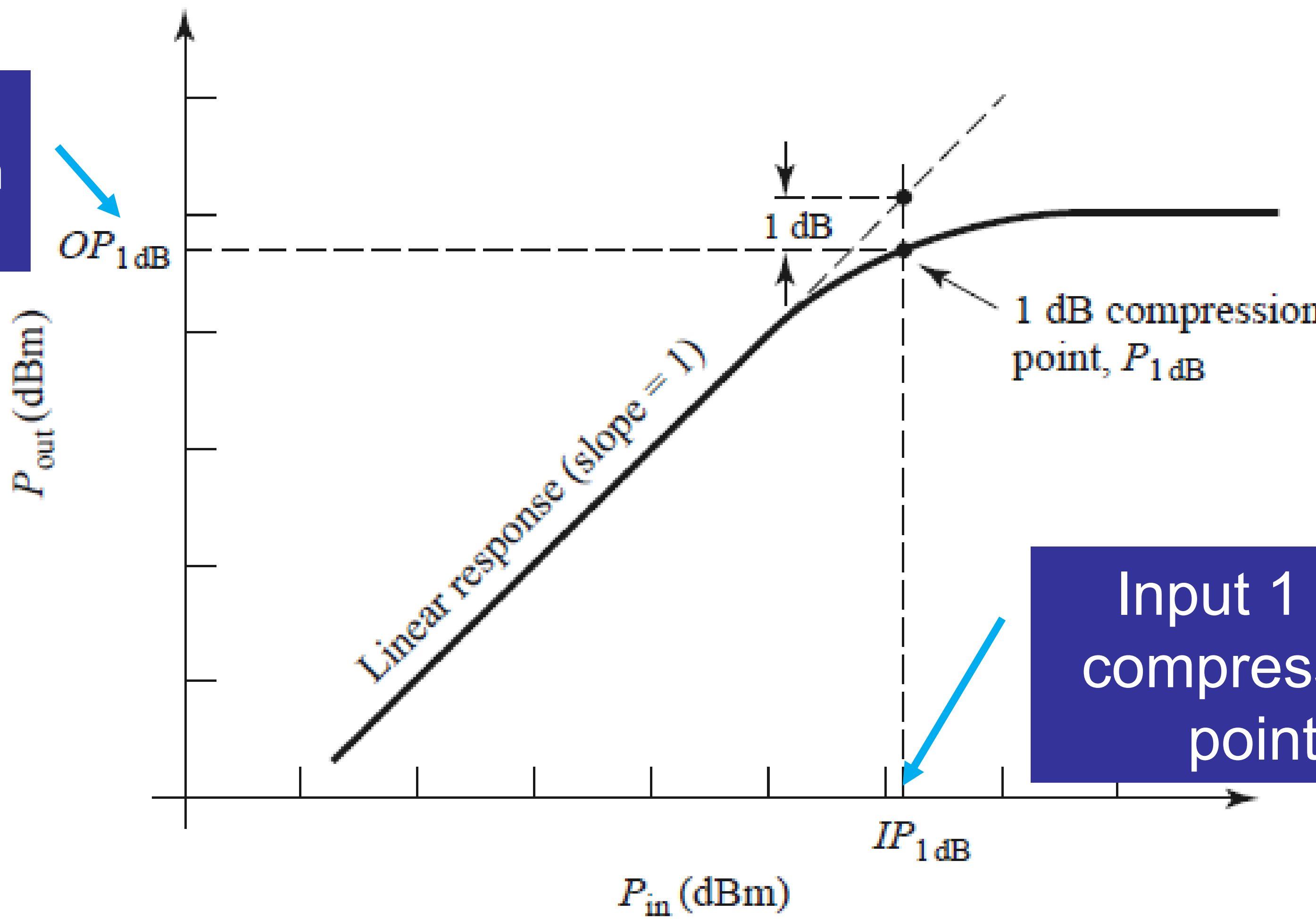
$$v_{out}(t) = v_{out,DC} + a_1 v_{in}(t) + a_2 v_{in}^2(t) + a_3 v_{in}^3(t) + \ldots$$

- Harmonic generation (multiples of a fundamental signal)
- Saturation (gain reduction in an amplifier)
- Intermodulation distortion (products of a two-tone input signal)

More info: book from B. Razavi, RF Microelectronics, chapters 2.1.1 and 2.1.2

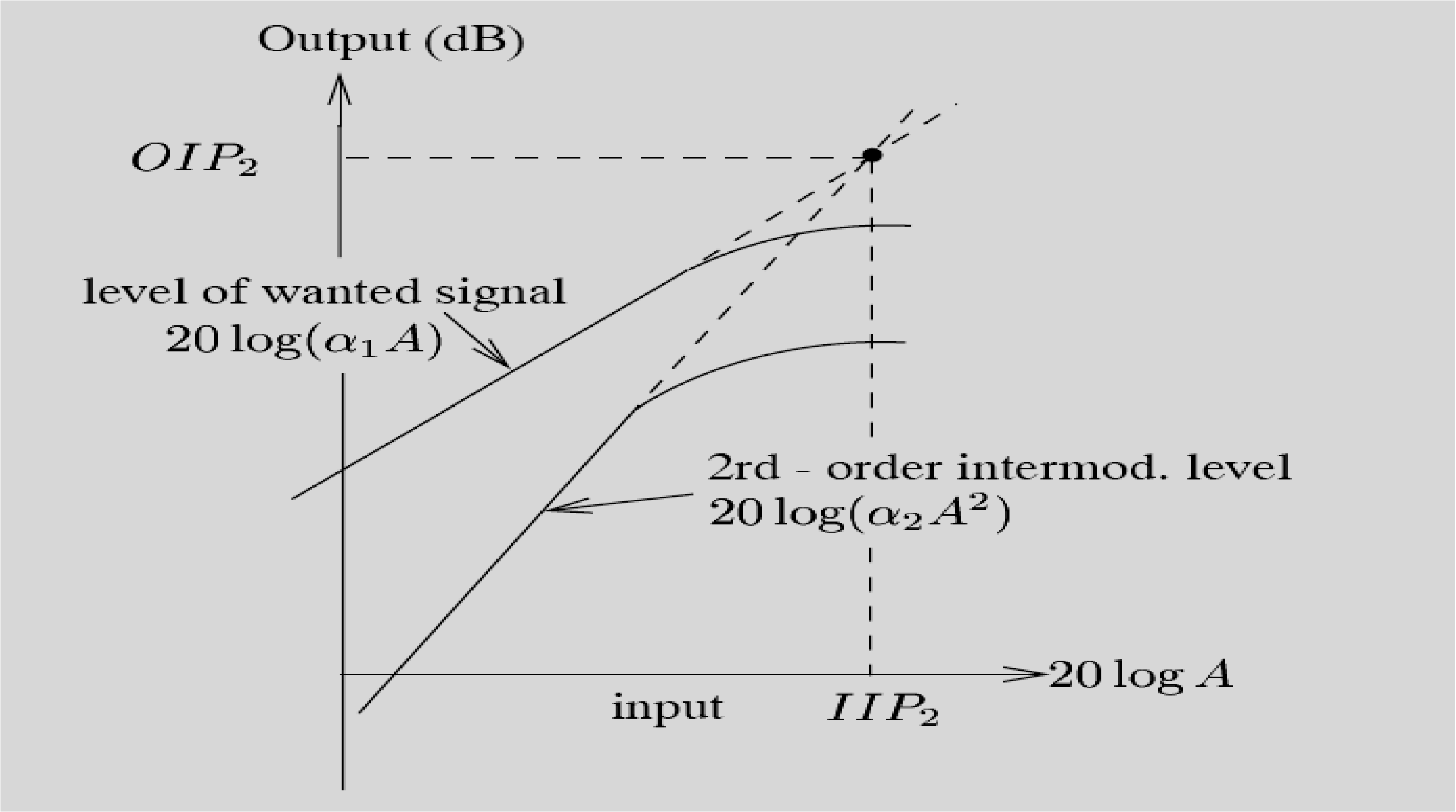
1 dB compression point

Output 1 dB compression point



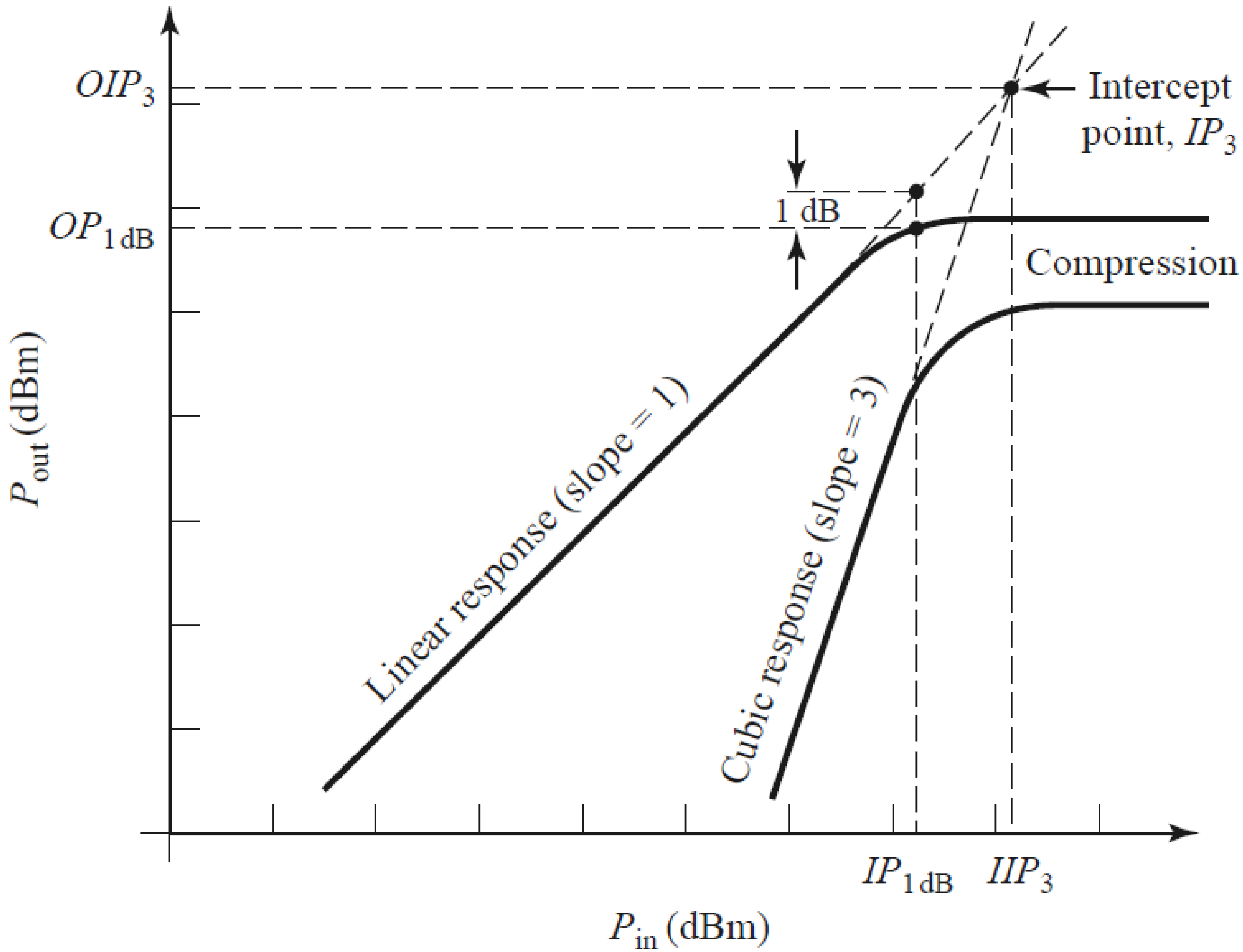
Input 1 dB compression point

Second order intercept point: IP2



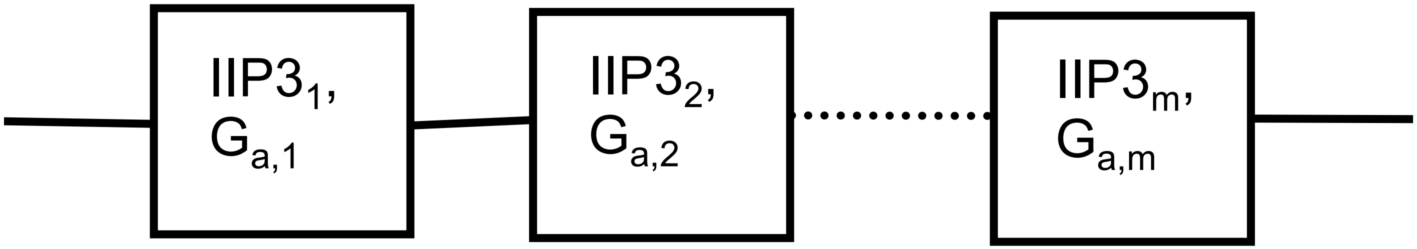
IIP2: input power where wanted power = second order power (extrapolated point).

Third order intercept point



IIP3: input power where wanted power = the third order power (extrapolated point).

Cascaded IIP3 formula



System with cascaded sub-systems with input IIP3 $IIP3_m$ and available gain $G_{a,m}$

$$\frac{1}{IIP3_{total}} = \frac{1}{IIP3_1} + \frac{G_{a,1}}{IIP3_2} + \ldots + \frac{G_{a,1}G_{a,2}\ldots G_{a,(m-1)}}{IIP3_m}$$

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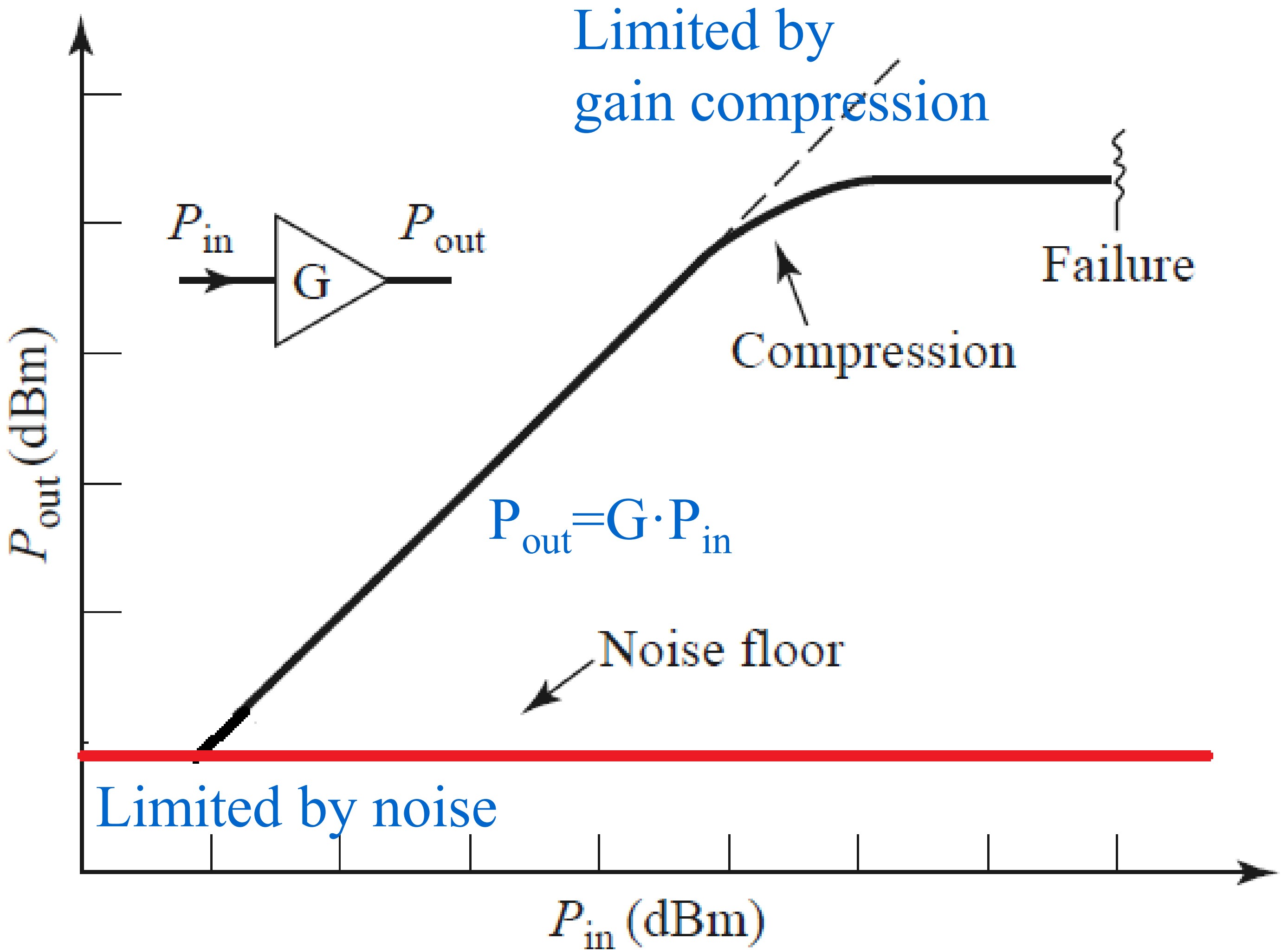
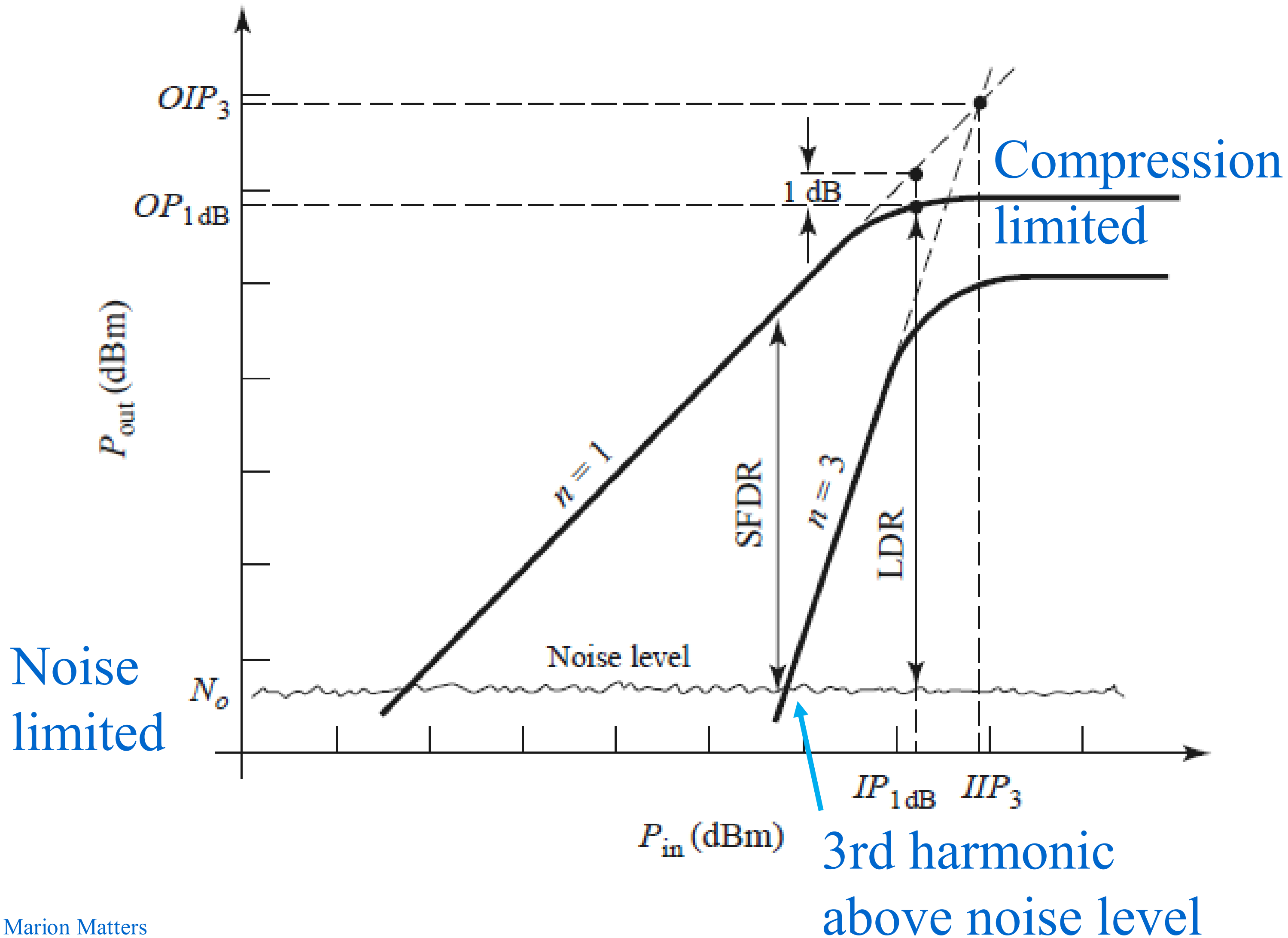
Dynamic range of an amplifier



Remark:
Gain in RF
is typically
power gain,
not voltage gain.
See also:
lecture week 5

Linear dynamic range (LDR)
Spurious free dynamic range (SFDR)



LDR and SFDR equations

- **Linear dynamic range: Output power difference between the 1 dB compression point and the output noise power:**

$$\mathrm{LDR}\,(\mathrm{dB}) = OP_{1\,\mathrm{dB}} - N_o$$

- **Spurious free dynamic range:**

$$\mathrm{SFDR} = \left.\frac{P_{\omega_1}}{P_{2\omega_1-\omega_2}}\right|_{P_{2\omega_1-\omega_2}=N_o} = \left(\frac{OIP_3}{N_o}\right)^{2/3}$$

$$\mathrm{SFDR}\,(\mathrm{dB}) = \frac{2}{3}(OIP_3 - N_o)$$

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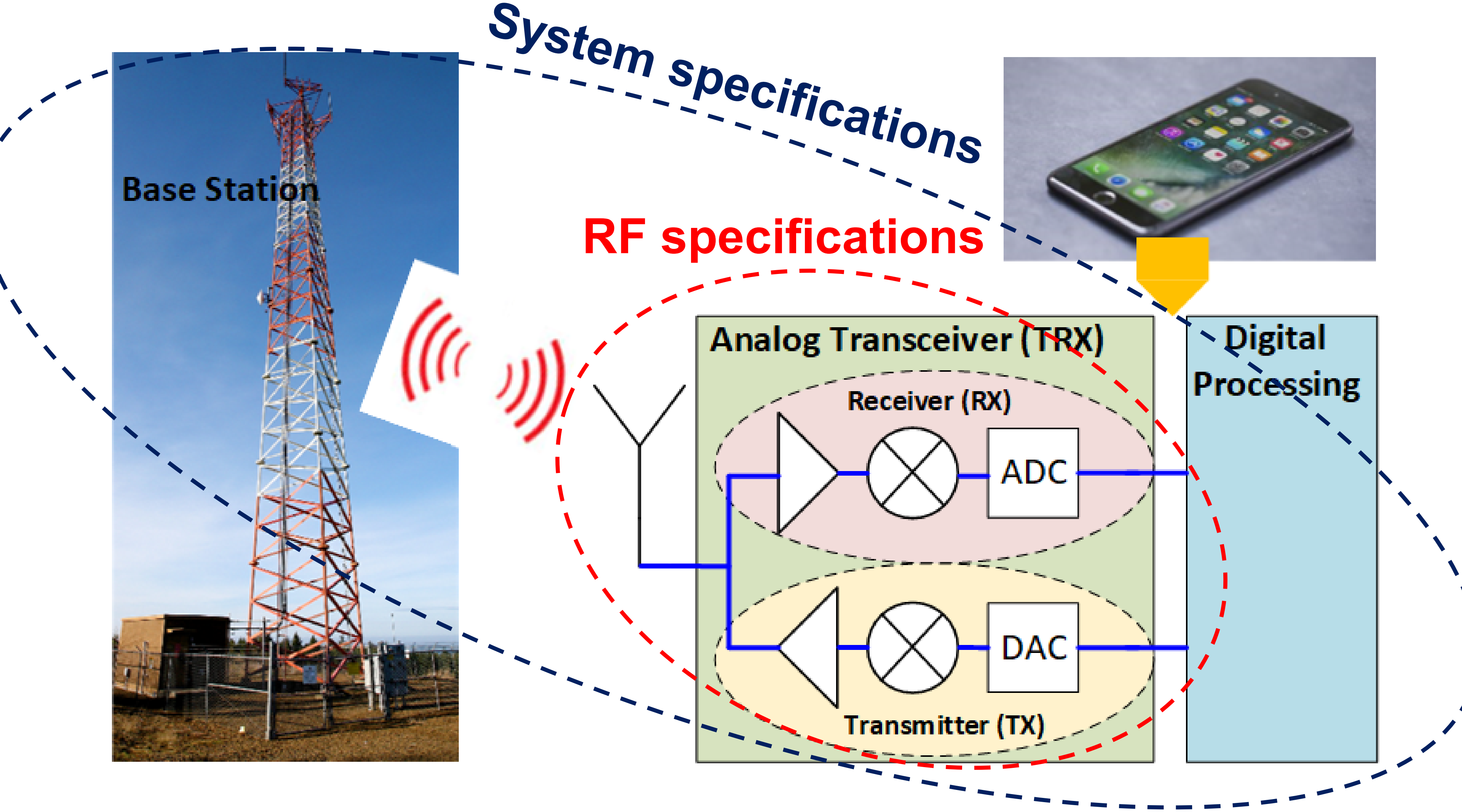
System aspects & consideration



System aspects & consideration

- Standards in wireless
- Modulation schemes
- Bit error rate
- Receiver sensitivity
- Link budget

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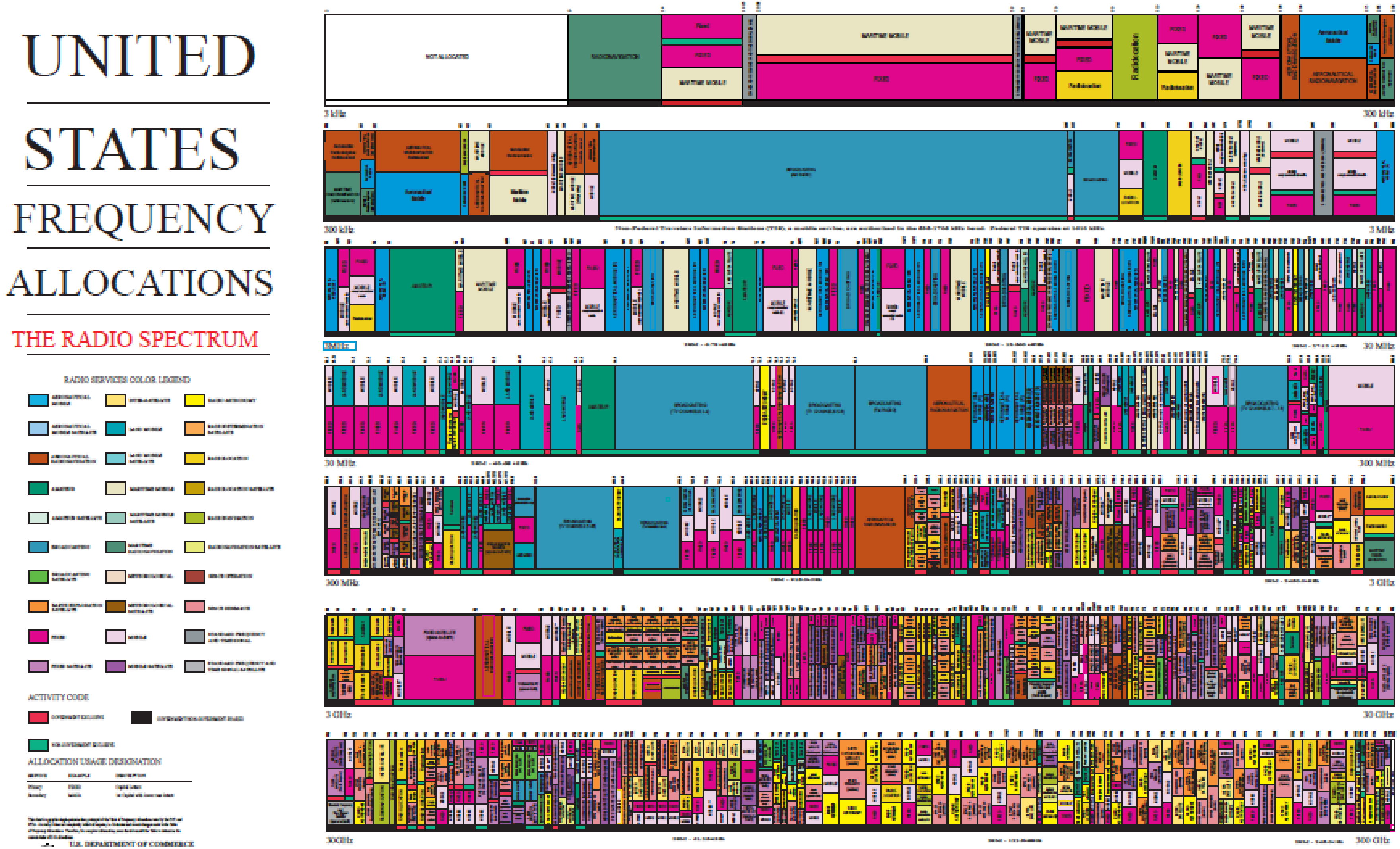
Frequency Allocation (info only)



https://www.ntia.doc.gov/page/2011/united-states-frequency-allocation-chart

Which wireless standards does your smart phone cover?

Connectivity	Cellular	GPS NFC FM radio
WIFI: 11b/g; 11ac Bluetooth (BT)	2G/3G/4G	
High data rates Up to 1Gbps Short link (cm – 30m)	Quality of Service Voice / data Up to few Mbps large link (km)	Specialties

Which cellular standards does your smart phone cover and why? (info only)

- **It all started with GSM900**
  - Global System for Mobile Communication
  - 2nd generation of digital cellular networks (2G)
  - Deployed in 1987
  - 900 refers to 900MHz, the operation frequency
- **In 1993 GSM900 was expanded to GSM1800**
- **In 1995 GSM1900 was created to allow fax, data and sms**
  - Short messaging service
- **In 2000 GPRS was launched**
  - General Packet Radio Service
- **In 2001 UMTS/W-CDMA was deployed**
  - Not part of GSM, Universal Mobile Telecommunication System (3G)

100M subscribes in 1998 – 500M in 2001

Which cellular standards does your smart phone cover and why? (info only)

- **In 2002 MMS became possible**
  - Multimedia Messaging Service
  - GSM800 was deployed
- **In 2004 EDGE was deployed**
  - Enhanced Datarates for GSM Evolution
- **In 2005 HDSPA launched to increase data rate further**
  - High speed Downlink Packet Access (3.5G)
- **In 2007 HSUPA launched to increase data rate further**
  - High speed Uplink Packet Access (3.5G)
- **In 2009 finally LTE**
  - Long Term Evolution (4G)
  - Combine GSM/EDGE with UMTS/WCDMA
  - 2013: LTE-A (LTE_Advanced)

500M suscribes in 2001 – 3B in 2008

Which cellular standards does your smart phone cover and why? (info only)

- So, a modern cellular phone covers LTE and to be backwards compatible also GSM
- Why? To enable high data rate in a cellular environment, i.e. large distance and with QoS
- It should be noted that the very first phones were using the 1G standard
  - Started in 1979 (Japan)
  - Analog modulation
  - AMPS (Advanced Mobile Phone System) – USA
  - NMT (Nordic Mobile Telephone) – Nordic countries, Netherlands

Mobile communication standards

Standard	Downlink Mbps	Uplink Mbps	Range km	Modulation	Access scheme
GSM GPRS	0.08	0.04	~26	GMSK	TDMA, FDD
GSM EDGE	0.47	0.47	~26	8PSK	TDMA, FDD
GSM EDEG Evolution	1.9	0.9	~26	32QAM	TDMA, FDD
UMTS WCDMA HSDPA	14.4	0.38	~200	CDMA	TDD, FDD, TDMA
UMTS WCDMA HSUPA	14.4	5.76	~200	CDMA	TDD, FDD, TDMA
UMTS WCDMA HSPA+	168	22	~200	64QAM,MIMO	TDD, FDD, TDMA
LTE	326	86	N.A.	OFDMA,MIMO	TDD, FDD, TDMA

LTE advanced (4G): 1 Gbps!

Increased data rate!

Which connectivity standards does your smart phone cover?

- **Wireless Local Area Network (WLAN)**
  - **IEEE 802.11 family**
  - **Started with 11b in 1999 in 2.4 GHz band**
  - **Moved to 11a in 2003 in the 5 GHz band with an derivative as 11g in the 2.4 GHz**
  - **A step up in data rate with 11n in 2009**
  - **To finally 11ac in 2013 (which is defacto now in the latest phones)**

Which <u>connectivity</u> standards does your smart phone cover?

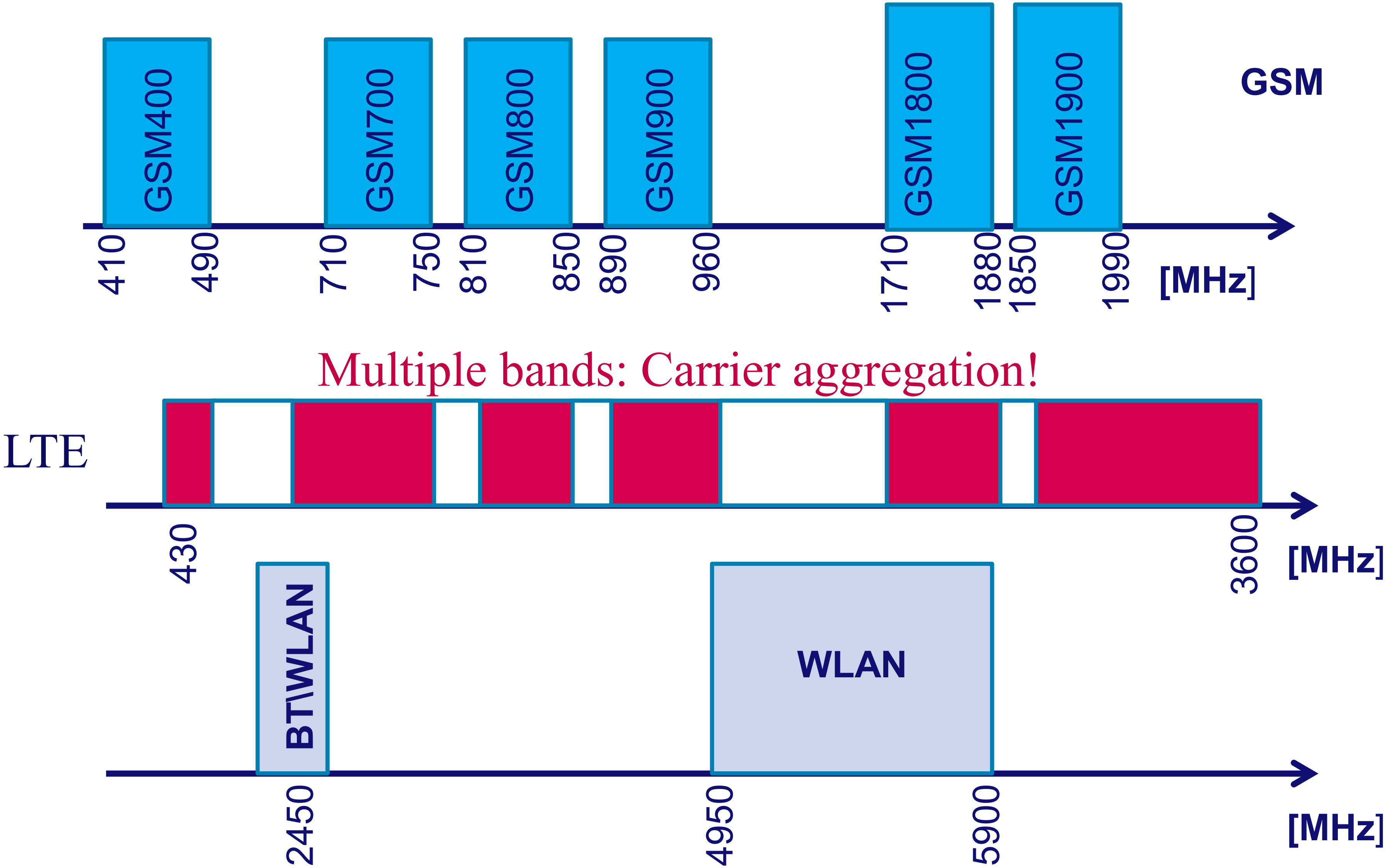
- **Wireless Personal Area Network (WPAN)**
  - **Bluetooth (BT)**
  - **Invented in 1994**
  - **IEEE802.15.1**

Wireless connectivity standards

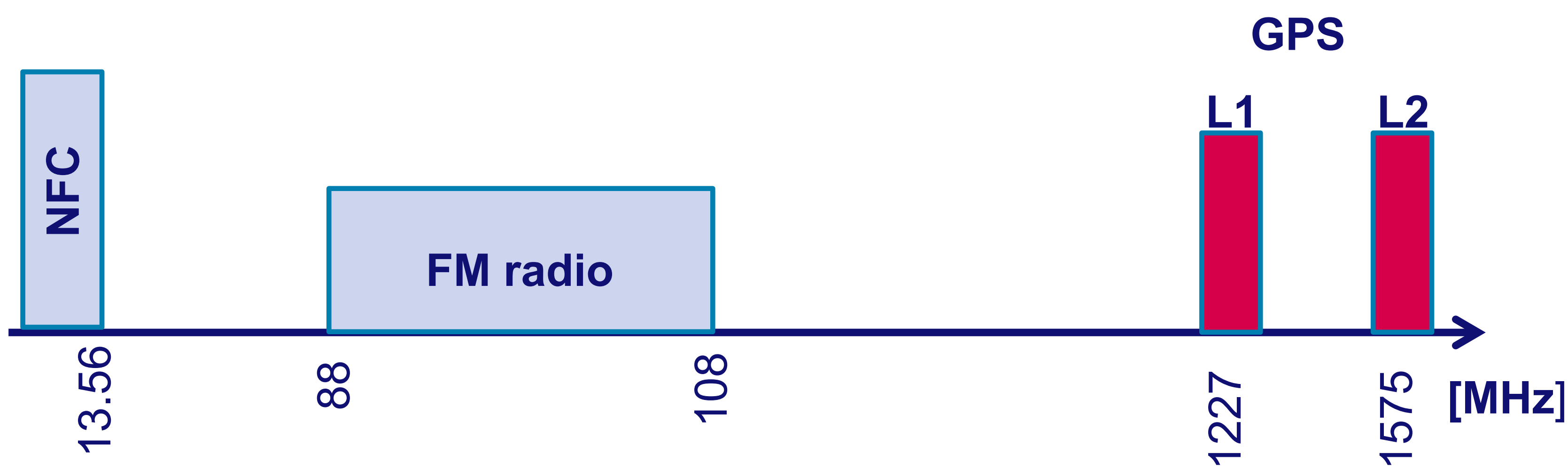
Standard	Data rate Mbps	MIMO	Range m	Modulation
802.11b	11	no	~26	GMSK
802.11a/g	54	no	~100	OFDM,64QAM
802.11n	150	4	~200	OFDM,64QAM
802.11ac	860	8	~200	OFDM,256QAM
Bluetooth (BT)	1	no	~100	GFSK
BT-EDR	3	no	~100	8DPSK

Increased data rate!

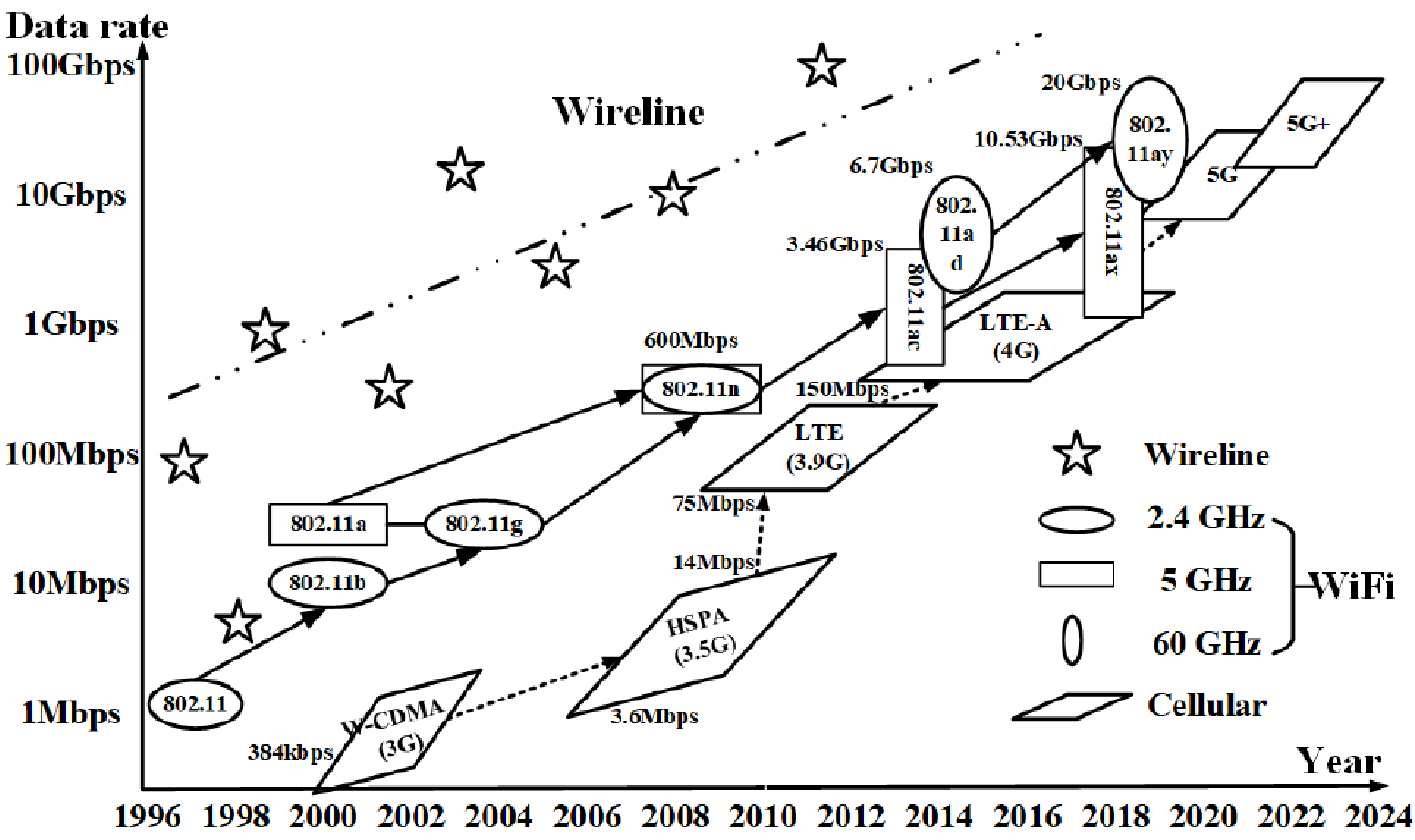
Which frequencies?



Which frequencies: other standards?



Communication data rates



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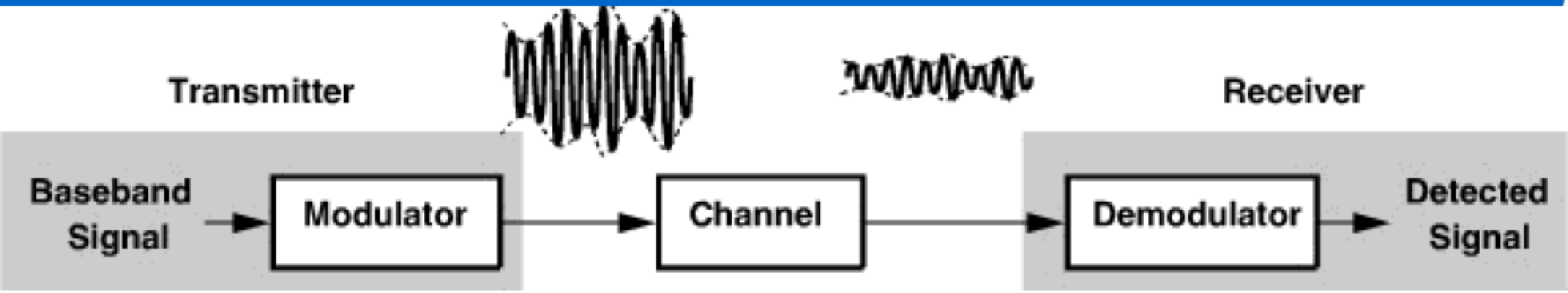
Modulation schemes: general aspects



The information is in the modulation, e.g. amplitude, phase, frequency
The carrier frequency does not contain the information

Transmitted signal: $$x(t) = a(t)\cos[\omega_c t + \theta(t)]$$

Important aspects of modulation:

1. **Detectability** (e.g. it's easier to distinguish between 0 and 1, than to distinguish between 8 different levels)
2. **Bandwidth efficiency**: How many bits per Hz bandwidth; limits the data rate and number of users
3. **Power efficiency**

Source: Razavi, RF Microelectronics

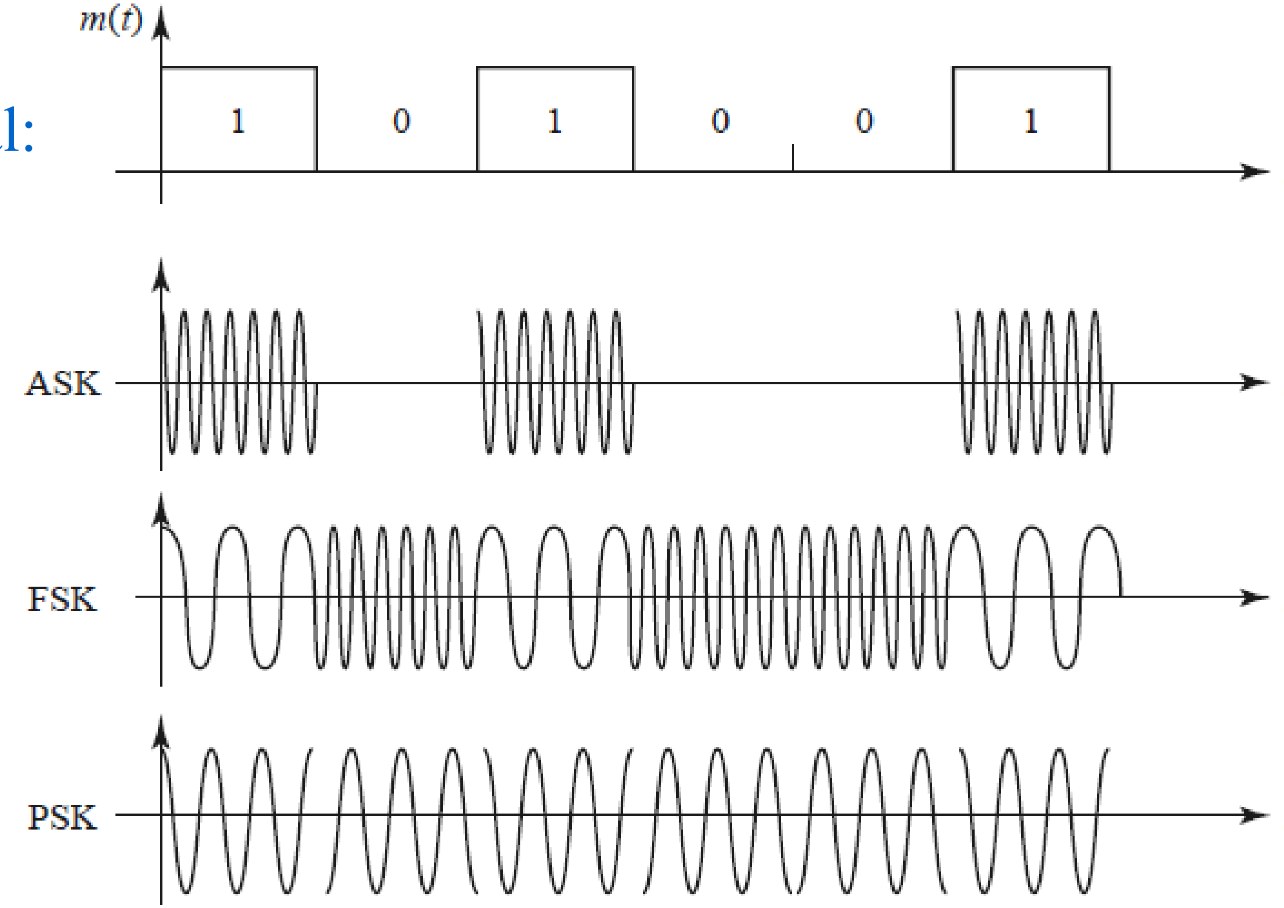
Digital binary modulation schemes

Digital baseband signal:

Amplitude shift keying:

Frequency shift keying:

Phase shift keying:



Higher order modulation schemes

- **Use 2^m levels of amplitude or phase of the digital signal to encode multiple bits at the same time Binary modulation: m=1**
- **Combine phase and amplitude modulation: quadrature modulation schemes, e.g. QAM-64**

Bit error rate

- Ideal case: The receiver detects the same bit as was transmitted
- Real case: Noise, interference, fading, multi-path lead to detection errors
- Bit error rate (BER, P_b): Probability of an error in the detection of a singel bit

The BER depends on
- the signal to noise ratio of the received signal
- the modulation scheme

Energy per bit and received noise power

General observation:
The probablity of detecting an error is smaller when the energy per bit E_b is higher and the noise power over the required bandwidth n_0 is lower.

Energy per bit:

$$E_b = S \cdot T_b = \frac{S}{R_b}$$

Received noise power

$$N = n_0 \cdot B_{required} \Leftrightarrow n_0 = \frac{N}{B_{required}}$$

n_0: Noise power spectral density

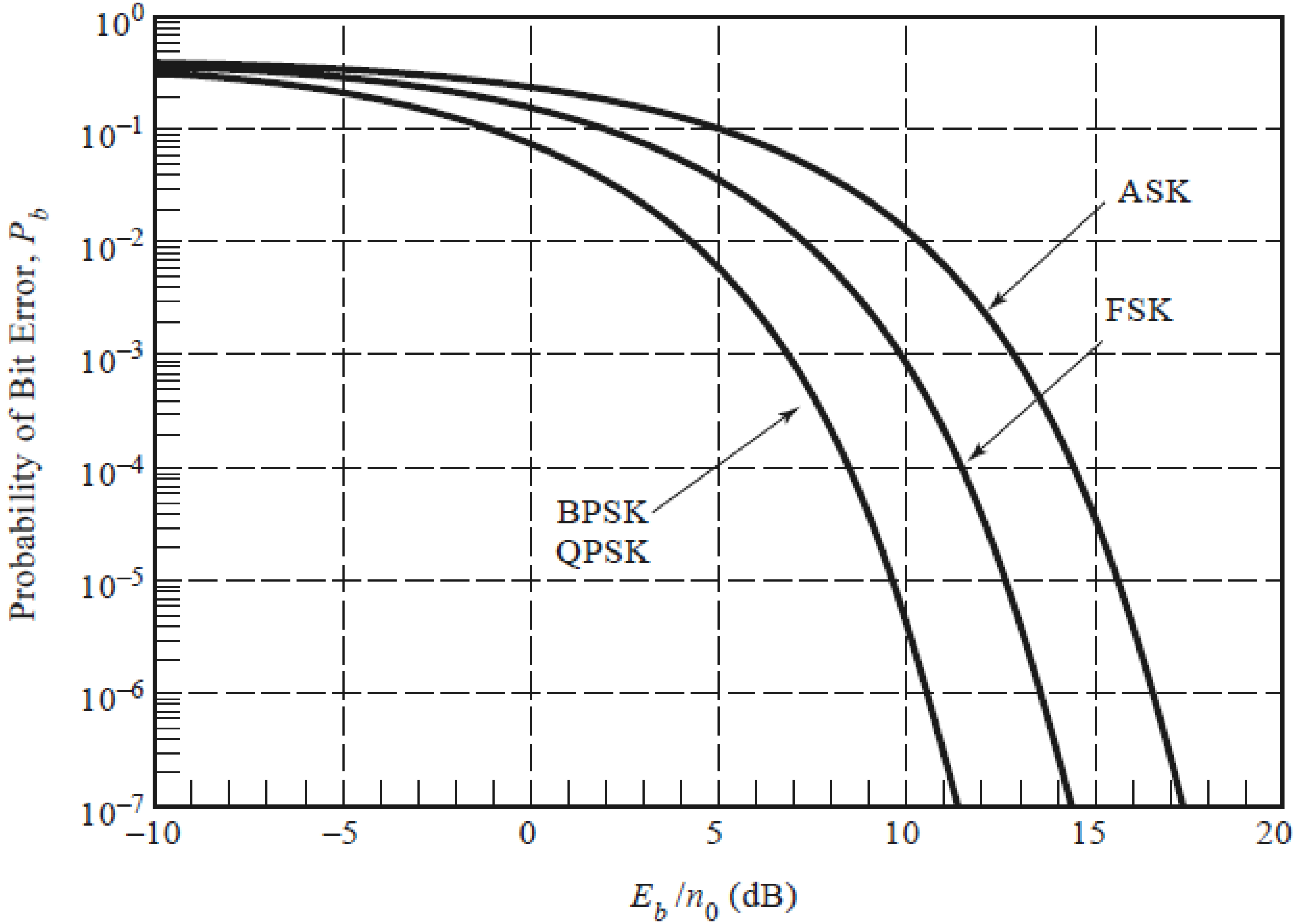
$$\frac{E_b}{n_0} = \frac{S}{N} \cdot \frac{B_{required}}{R_b}$$

Required bandwidth of the receiver

Data rate

Signal to noise ratio

BER as a function of E_b/n_0



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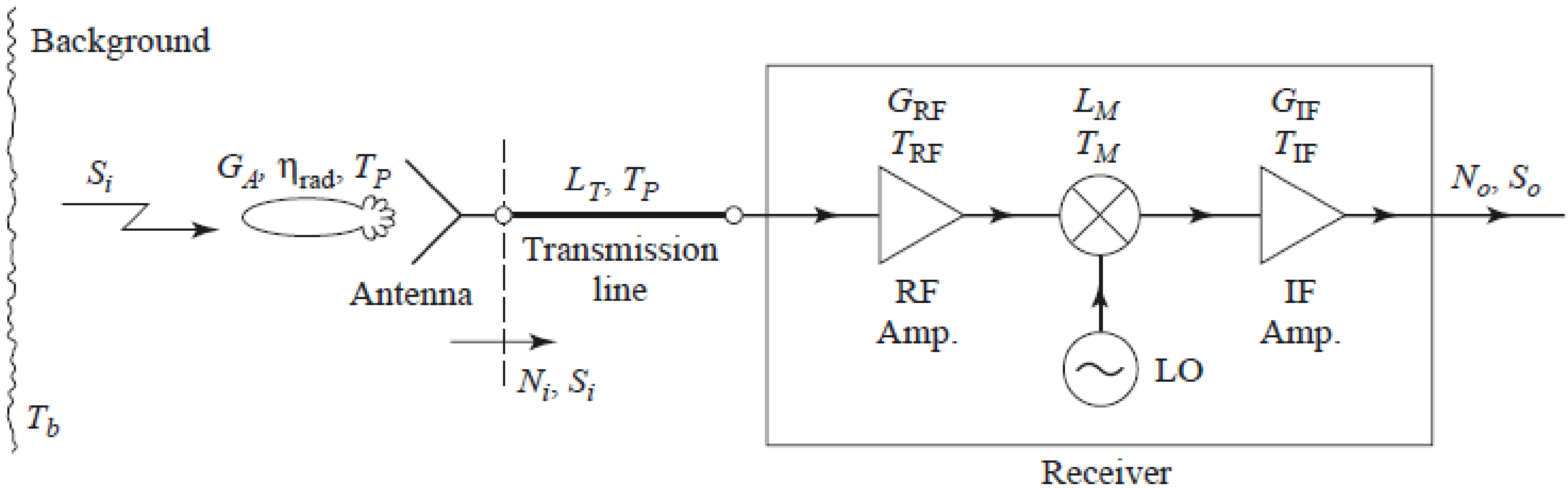
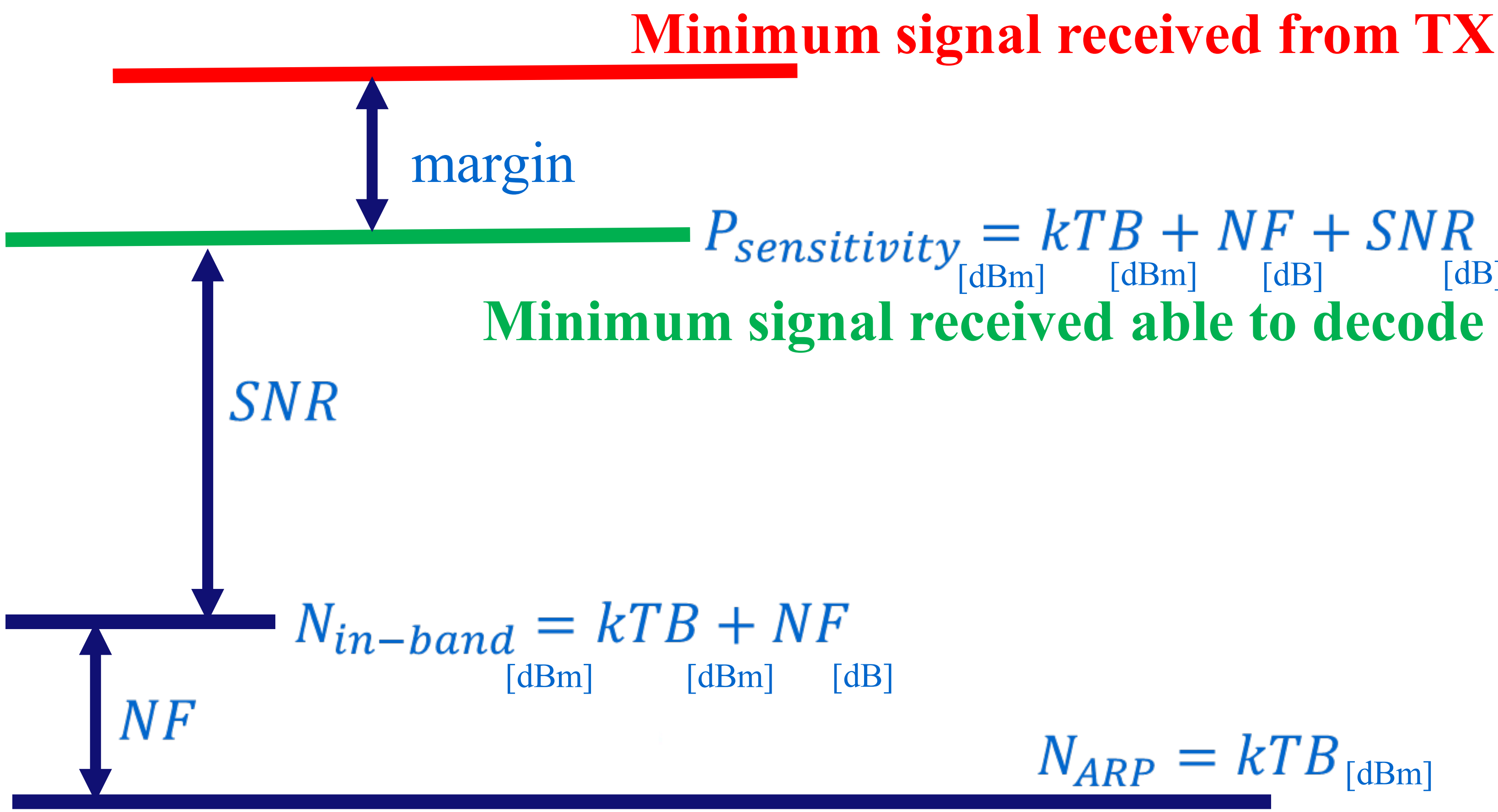
Receiver sensitivity



- RX sensitivity refers to the minimum received signal the receiver can still decode, i.e. extract error-free the data/voice
- Clearly noise comes into the picture as well as bit-error-rate (BER) and thus signal-to-noise ratio (SNR)

Receiver sensitivity in dBm: graphical representation



Receiver sensitivity: Equation

- **The minimum power signal level**
- **that a system can detect**
- **with an acceptable SNR/BER:**

$$P_{sensitivity} = P_{Rsource} + 10\log(B) + NF + SNR_{\min,out}$$

With:

$P_{Rsource}$: the noise of the source resistance:
-174 dBm/Hz (kT) assuming an input power match.

$SNR_{min,out}$: the minimum SNR at the output of the front-end
(e.g. at the input of the demodulator),

B: effective system bandwidth for integrating noise

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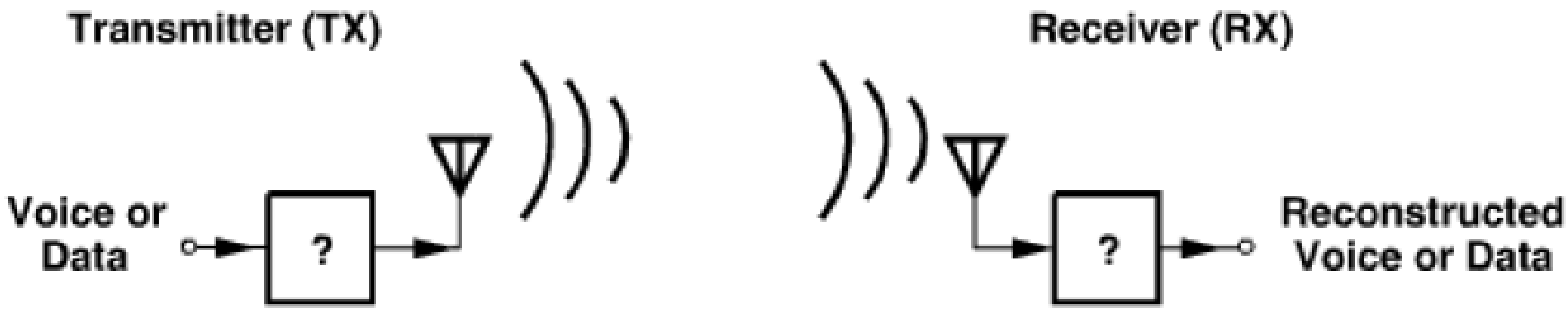
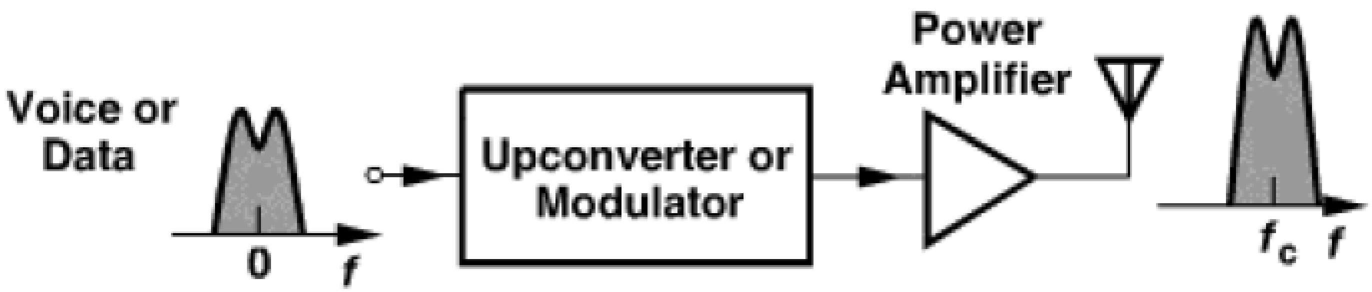
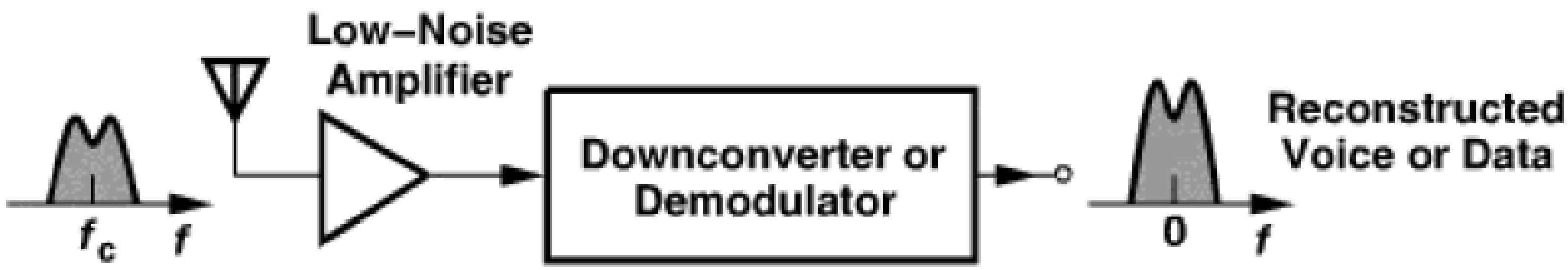
System perspective



Transmitter:

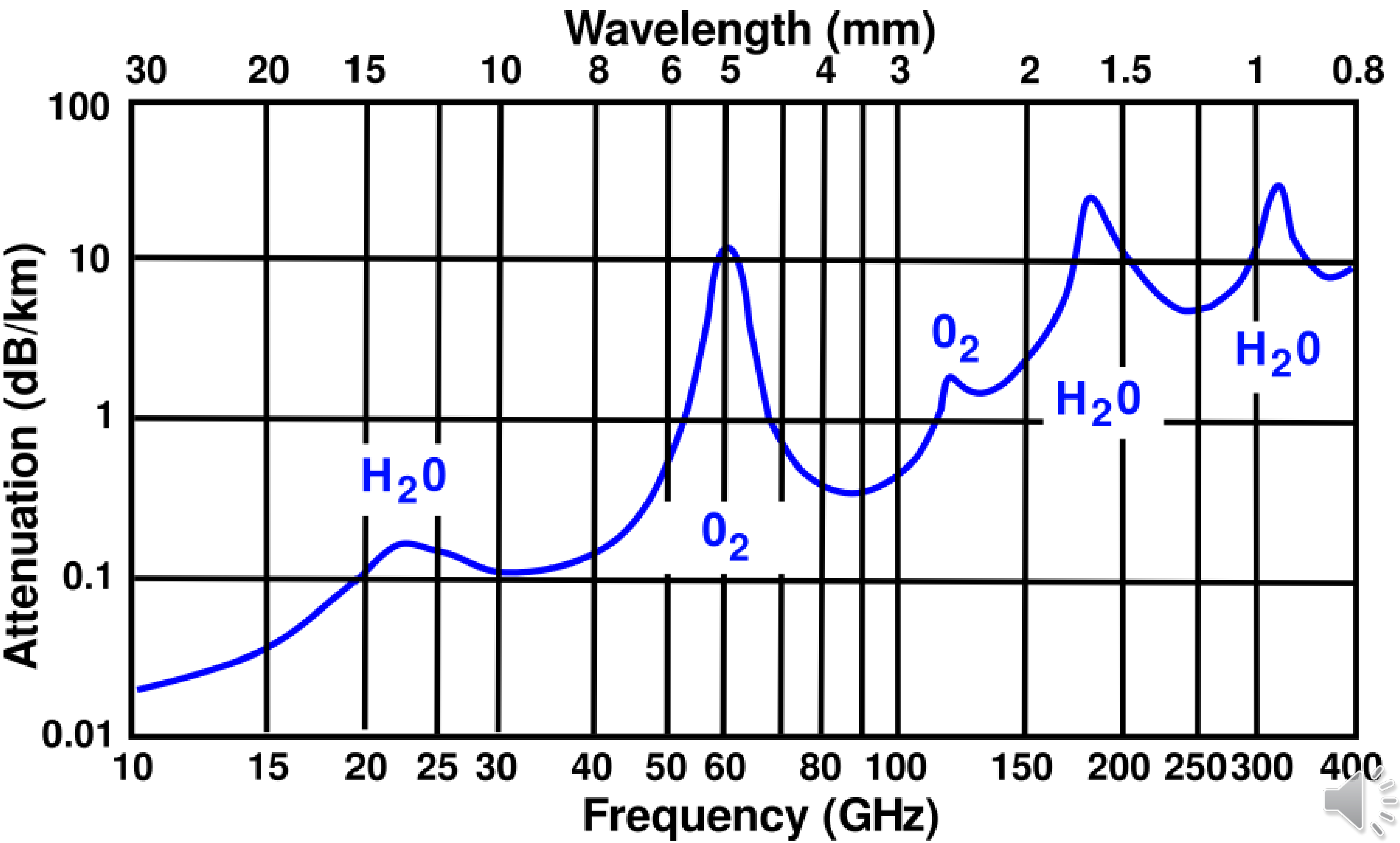


Receiver:



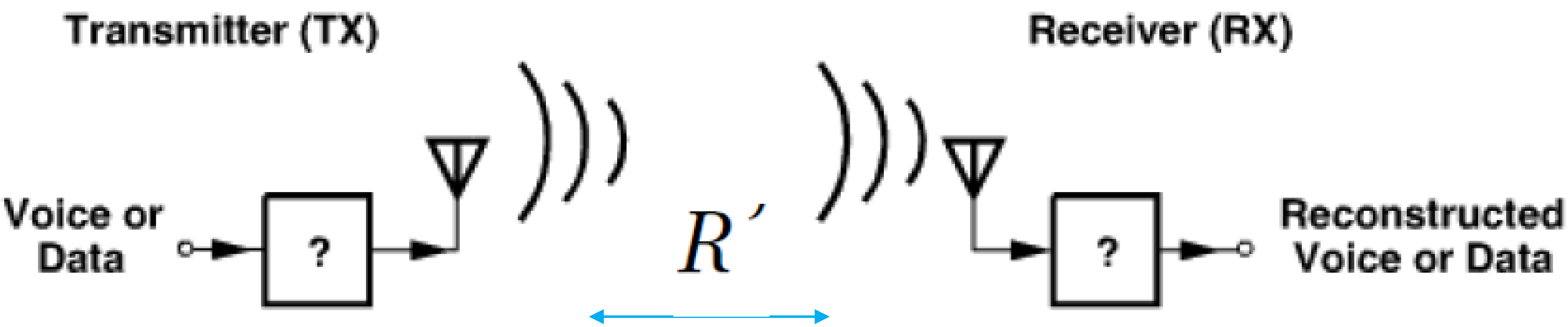
Figures from Razavi, RF Transceivers

Atmospheric attenuation



Friis radio link formula

$$P_{Rx} = P_{Tx} \cdot G_{Tx} \cdot G_{Rx} \cdot \left(\frac{\lambda}{4\pi R}\right)^2$$



P_{Tx} - TX output power

G_{Tx} - TX antenna gain

G_{Rx} - RX antenna gain

P_{Rx} - Power at RX input

λ - wavelength

SNR and Shannon

- **There is an upper limit on data rate (C) set by the signal to noise ration (SNR) and bandwidth (B):**

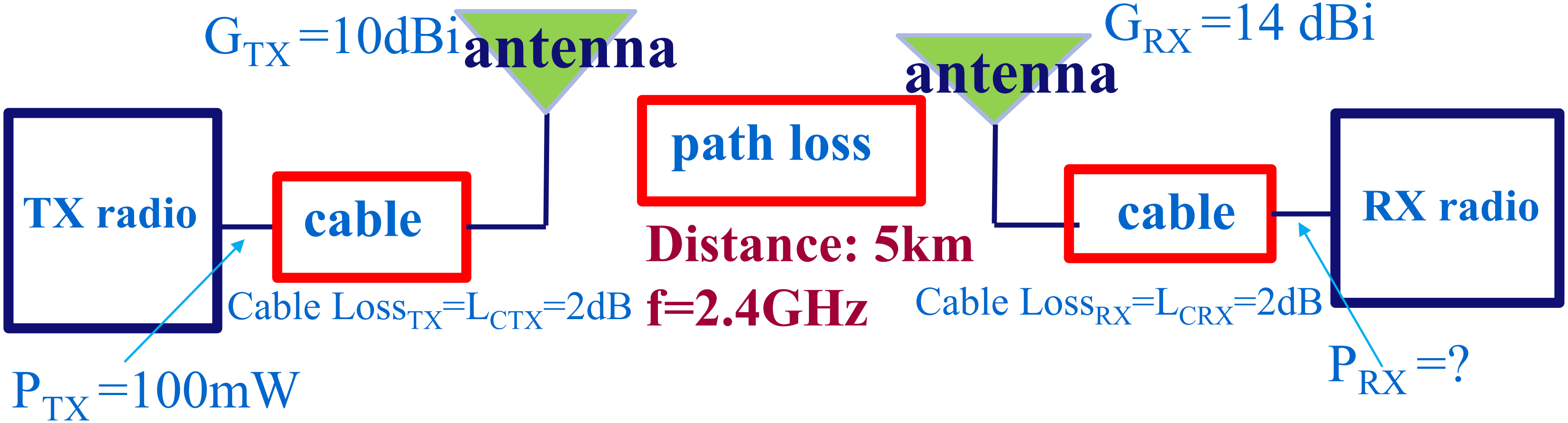
$$\boxed{C = B*\log_2(1+SNR)}$$

$$C = BW \times \log_2(1 + \frac{P_{Rx}}{N_{in}})$$

$$P_{Rx} = P_{Tx} \cdot G_{Tx} \cdot G_{Rx} \cdot (\frac{\lambda}{4\pi R})^2$$

$$N_{in} = k_b * BW * T * F$$

Exercise: Calculate the received power



Transmit power	**P_{TX} =20dBm**
Transmit antenna line loss	**L_{CTX}=2dB**
Transmit antenna gain	**G_{TX} =10dBi**
Path loss (free-space)	**114dB @ 5km @ 2.4GHz**
Atmospheric attenuation	negligible
Receive antenna gain	**G_{RX} =14dBi**
Receive antenna line loss	**L_{CRX}=2dB**
=P_{RX}	**-74dBm**

Summary

Antenna system aspects → Link budget → Received power

Noise → kTB, NF, T_e Limited Receiver sensitivty

Distortion → P_{1dB}, → LDR

IP_2, IP_3 → SFDR Limited SNR

Digital modulation schemes → ASK PSK FSK QAM → Channel capacity → BER